December 15, 1993

Dr. Schibly
Program Manager
Submarine & Diving Medicine
Naval Medicine Research and
Development Command
National Naval Medical Center
Bethesda, Maryland 20889-5044

Dear Dr. Schibly:

Please find enclosed my final progress report for the ONR contract (N00014-89-C-0103) "Divers swimming efficiency as a function of buoyancy, swimming attitude, protective garments, breathing apparatus, swimming technique and fin type". I am not sure if your are still my contact person, or if this is the correct address,however I have not been informed of any change so I am submitting this report in your name.

This report covers the entire portion of the grant period. As a reminder I was granted a one year extension of this grant, as the funding started six months after the initial starting date. I have submitted regular progress reports, so I will stick to what I consider the "milestones" of our work.

The overall purpose of this series of studies was to determine the energy cost of underwater swimming and the effects of:

1) buoyancy and body position
2) fin selection
3) Swimming time
4) body cooling
5) protective garments
6) breathing gear

on the over all energy cost. Of the 6 goals orginaly proposed, 5 were accomplished.

The effect of breathing gear selection was not fully analyzed. Our experiments consisted of single and two house regulators on standard cylinders. I attempted to get access to the types of Navy diving breathing gear by visiting and communicating with the Navy Bases that were recommended to me. In addition I worked through the Naval Medical Research Institute (Diving Medical Technology), Bethesda and the Diving Research Center in Pannama City Flordia. Unfortunately the breathing gear was not made

available to me and therefore could not be tested in our facility.

The report is organized as outline above, however, as the energy cost of underwater swimming is speed dependent, swimming velocity is presented first. Another aspect of the present study was the development of and use of a new breathing system for collection of expired gas. The latter technique will be discussed under another section. Final data for two experiments that were conducted outside the proposed and funded work are presented as they may be of interest to the Navy. Extension of the work of the latter two studies to underwater swimming were proposed by not funded.

The publications resulting from these studies include 4 abstracts presented at the Undersea Biomedical Society. Several papers were submitted to Dr. Peter Kent for approval and submitted to the Journal of the Undersea Biomedical Society. These papers were reviewed, and the reviewers asked that the specific gear we used be named. Dr. Kent placed as a condition for publication that we not mention specific names of equipment. These paper have not been resubmitted to this or any other journal at this date.

Sincerely yours,

David R. Pendergast.
Professor of Physiology

FINAL PROGRESS REPORT

ONR Contract Nooo14-89-C-0103
TITLE: Divers Swimming Efficiency as a function of Buoyancy, Swimming Attitude, Protective Garments, Breathing Apparatus, Swimming Technique and Fin Type"

INTRODUCTION Underwater swimming requires an oxygen consumption that is determined , in part, by the divers swimming speed. At a given speed the energy cost is determined by the body drag of the diver (including his gear) and the overall net mechanical efficiency of swimming. Unlike running, where the drag is minimal and efficiency is similar for all individuals (energy cost =38 mlo2/kg/mile), the energy cost of underwater swimming varies greatly between swimmers and is dependent upon their technique. There is no way for the diver to "sense" his energy cost of swimming with different speeds or gear, and infact they often draw the wrong conclusion. In addition, a small difference in the energy cost to swim 1 km, becomes important when the swimming distance (or time) is long. These two factors have relevance in mission exercises.

In a previous study (E.Lanphier) using Navy divers and unspecified gear the drop in bottle pressure was used as a method of determining the oxygen consumption of swimming as a function of speed. These data are shown in Figure 1. The range of speeds was from 0.3 to 0.625 m/sec. The values for the average and minimal and maximal values are shown in the graph. The v02 increased exponentially with speed. If we divide the Vo2 by velocity we can calculate the energy cost per unit distance (lo2/km). The vo2/d increased from 50 l/km at 0.25 m/sec to 54 l/km at 0.46 m/sec to 68 l/km at 0.625 m/sec. From the overall economy stand point, swimming above 0.45 m/sec cost proportionally greater than below, however the difference between 0.45 m/sec and 0.25 m/sec is minimal. The optimal speed in underwater swimming should be selected based on the Vo2/d as well as the Vo2 as a percentage of Vo2 max.

Based on the data from this study and discussions with the Navy Personnel we selected three speeds to conduct further experiments (30.8,40.6, and 53.4 m/min). Prior to presentation of the data, a short discussion of methods would appear appropriate. Unless otherwise noted, the equipment used in these studies was:

standard two house regulator, face mask, total body dry

suit, PFD, SCUBA weight belt with about 10 lbs of lead weights, fins (freely selected by the subject), single tank in a standard frame.

The water temperature was maintained at a thermal neutral temperature for a wet suit clad swimmers swimming at a moderate speed.

MEASUREMENT OF OXYGEN CONSUMPTION

Previous studies have used the drop in tank pressure to determine the oxygen consumed. This technique is best used when breathing pure oxygen, which was not the case in our experiments.
This method, requires longer collection times and is hard to perform in changing experimental conditions and does not provide data for ventilation or carbon dioxide production. Although some of these limitations can be corrected we used a different and new approach carbon dioxide production and ventilation can not be obtained. We used a pressurized bag and box system that allowed collection of expired gas from divers. This method allowed the calculation of VE, Vo2, and VCO2. These data when combined with measurements of venous blood lactic acid, allowed the evaluation of the metabolic system used during underwater swimming as well as the substright burned. See appendix A for a description of this method.

MEASUREMENT OF BODY DRAG AND EFFICIENCY:

In previous studies in our laboratory, we developed a method of determining the body drag and efficiency of swimmers while they were actually swimming. This technique is based on measurements of sub-maximal oxygen consumption. The drag determine during actual swimming is two to four times greater than drag determined by towing an inactive subject (passive drag). As drag and efficiency are the two primary determinants of the energy cost of swimming understanding them is critical.

From the practical stand point our studies showed that body drag is dependent upon the frontal cross-sectional area and the speed. Of course minimizing these would reduce energy cost. The factors to be consider are:

1. the size of the body plus the equipment
2. the body position with reference to the horizontal (body attitude)
3. the excursion distance (top of kick to bottom)during the kicking phase
4. speed of swimming

The overall net mechanical efficiency is determined by the energy cost of swimming as a ratio to the body drag and swimming speed. These two variables are independent of each other. For practical purposes our experiments have show that the net mechanical efficiency is to a great extent based on the kicking frequency. At a given drag the propulsion force is determined by the kicking

frequency and the force that is applied per kick. The latter variable can also be expressed as the distance that the body travels per kick. The force per kick, is inturn, dependent upon the force generated by the muscles used in kicking and the transmission of that force to the water via legs and fins. The force therefore is also influenced by the depth of the kick. One could summarize this by saying, in general, a kick that is deep would have a slow frequency, thus a higher efficiency but also a higher drag. By contrast a kick that had a reduced depth and higher frequency, would have a lower drag but also a lower efficiency. As the energy cost of swimming is dependent upon the ratio of drag and efficiency the depth and frequency of kicking has to be optimized. The optimization of the leg kick is, in part, dependent on the effectiveness of the fins, which is influenced by the fins size, weight, length and the material it is made from. The leg kick during fin swimming is primarily a up-down movement in a single plane and therefore we analyzed the depth and frequency of kicking from a single video camera filming a side view of the diver as he/she swam past three underwater windows.

EFFECT OF SWIMMING SPEED

The average data and their standard deviations for the Vo2 for underwater swimming at the three speeds used in these studies are shown in Figure 2. The Vo2 increases with increasing speed, and at the highest speed the Vo2 approached 85% of the maximal aerobic power of these swimmers. These swimmers could only sustain 53.4 m/min for 8-12 minutes, while they could sustain 40.6 m/min (60% of Vo2 max) for up to 2 hrs. Navy divers may have higher Vo2 max levels, but the relative % of Vo2 max that they could swim at should be comparable to our swimmers. The other factor that is important for long duration swimming is the energy cost to swim a given distance. This value can be expressed as the energy cost (Vo2) to swim a distance (Km). For the data in Figure 1, the Vo2/d for speeds of 40.6 and 53.4 were 40 and 42 l/km respectively. These two speeds had lower values for Vo2/d than the slower speed (47 l/km at 30.8 m/min) and significantly l;over values than for a slightly higher speed (65 l/km at 60 m/min). As will be described later in this report the addition of larger equipment and/or a dry suit or body cooling increases the Vo2 and Vo2/d significantly at the higher speeds, however the effect was not significant at low speeds (30.8 m/min). Speed selection during missions should consider all of the variables described above.

As compared to land activities the energy cost of swimming is greatly variable between subjects. The cost of swimming for an unskilled swimmer (even if his is a professional) may be two fold greater than a skilled swimmer. The importance of the kick frequency and depth has to be explored for each swimmer as to minimize the frontal surface area and frequency at a given speed (with a given gear configuration). It can not be emphasized sufficiently that subjects do not have a sense of their energy cost or what minimizes their cost of swimming. For example of 15

fins studied the fin most liked by the male divers was the one with a highest energy cost of swimming.

Another factor of interest is the substright used during swimming (as judged from the expiratory exchange ratio, R). Analyzing these data clearly indicate that for all investigated speeds, fat is an important contributed, and infact as important as glycogen/carbohydrates. Previous studies have indicated that the key issue is inter-muscular fat and glycogen, as it is what is used during exercise. This suggests that a diet should have sufficient fat and carbohydrates ,on a day-to-day basis, to maintain inter-muscular glycogen and fats during training and performance. This was demonstrated by a study in running where the endurance time increased over 20% and the Vo2 max by 10% when runners were given a diet with 35% fat. Experiments conducted by collages of ours in dogs and pigs indicated the improvements we observed in human could be improved further by increasing the fat content to 50-65 % of the food intake. The application of these data to divers where absolute Vo2 is low and swimming duration is long and in cold water is very promising. Experiments to pursue this hypothesis in divers are needed, however we were not re-funded to complete these ex[eriments.

In another series of experiments prolonged swims (up to maximal for our subjects, 2 hrs) suggested the mechanisms of failure in endurance swimming. Further experiments are needed to insure the importances of each parameter. The first observation was that the V02 to swim at a fixed and submaximal speed was constant over 105 min of a 120 min swim with the values rising about 10% during the failure part of the swim. The video indicated that during this latter phase the subjects had difficulty maintaining the kick frequency and depth that had been constant up to that time. Their body position was erratic during the fatigue part of the swim. Over the time of this swim the blood lactic acid was increasing, however the final value (for the whole body) was not high enough to alter the physiology. Likewise heart rate increased over the period of the swim but was still below a level that would be limiting. These data imply that the limitation to swimming endurance was in the peripheral muscles themselves. This could be termed local muscle fatigue and could be due to muscle fatigue, metabolic fatigue or substright depletion. Based on our protocols and measurements we can not identify the specific cite of failure. Additional experiments are needed to clarify these issues, however we were not re-funded to do these experiments.

BODY SIZE AND EQUIPMENT

It is clear from hydrodynamic equations that the frontal surface area is the primary factor that effects the energy cost of swimming at a given speed, and the maximal speed that divers can achieve. There are two important factors in determining the frontal surface area, the first is the surface area of the diver and gear when the diver is in the swimming position. The second is the swimming position, which in turn is determined by the

buoyancy of the diver/gear and the distribution of the buoyant and sinking forces in relationship to the center of gravity (essentially at the navel).

The combined effects of sized and buoyance was shown in our study comparing the energy cost of underwater swimming in men and women. The women were smaller and more buoyant and their energy cost was 140 Kcal/Km compared to men who had a cost of 225 Kcal/Km. The primary cause of these differences was buoyancy and it distribution in regards to the center of gravity. This effect was tested by varying the underwater weight (counter balancing weights worn by the divers) and the placement of the weights on male divers while they swam at three speeds. By distributing weights between the chest, waist, knee and ankles the torque (rotational force about the center of gravity) could be changes by 40 Nm and the body position (while not swimming) varied from the horizontal(20 degrees). During swimming the subject had to overcome the added drag of being less horizontal in the water or kick more to minimize drag. The latter option resulted in a reduced mechanical efficiency. The energy cost of swimming increased by 30-40% when the torque was increased. The important message of this study is that in designing or using equipment its size and its effect on the body position should be addressed and the diver should be kept as horizontal as possible in the water during swimming. This may imply that during non-swimming his body position should be about 10 degrees from horizontal with the feet above the head, so that when kicking starts he becomes more horizontal in the water.

The second factor in determining the energy cost of swimming is the size of the body/equipment as it effect the frontal surface area. As we were limited in the equipment we had available to us we could only compare swimming with a single vs double SCUBA tank configuration. We swam subjects at increasing speeds from 30.8 m/min up to maximal, which was 50.4 for the single tank and 45.5 for the two tank set-up. The latter may be similar in size to the Navy closed circuit breathing systems. The weigh placement was optimized (as described above). At low speeds (less than 35.7 m/min) there were no differences between one and two tanks, however at faster speeds the extra tank increased the cost of swimming by 25% and the increased cost was due to a higher kicking frequency. This presents a problem for speed selection as the Vo2/d for the slowest speed is high, so to minimize the effects of increased frontal surface area caused by added gear these subjects should have swam at 35.7 m/min. The take home from these data is that the more equipment that is added to the diver (increases his surface area), the more care has to be paid to maintaining a horizontal position.Another aspect of equipment selection is the type of fin to be used as it may influence the factors described above.

FIN SELECTION

The present study investigated 15 different types of fins. The results of the individual studies appear in previous

quarterly reports. This summary is designed to give practical application to our interpretation of our studies. The fins studied varied in weight from 0.9 to 1.82 Kg with the average being 1.23 kg. Weight per se did not significantly effect the Vo_2, however the best fins had weights of about 1.0-1.2 kg. The surface area of the fins varied from 175 cm^2 to 300 cm^2, and there was a tendency for the larger fins to have a greater energy cost. The larger fins however were also more rigid, and the rigidity was determined to be the cause of the greater energy cost. The fins with the least energy cost had the greatest flexibility built into them. An alternative to great flexibility is to place vents to minimize the resistance during the up-stroke. Fins with or with-out vents (with similar other characteristics) did not have varying energy costs, leading us to conclude that vents did not have a significant effect on Vo_2. The surprising observation about fin selection is the lack of difference between most of the fins. Our conclusion is that the best fin is not yet available, and of the ones that are only the very large,heavy and rigid fins were not economical (cost 20-40% greater than the other fins). Of the remaining fins diver preference may be more important than the minimal effects of fin selection on cost. We propose that the best fin would be a narrow, long and flexible fin with a closed foot pocket. The exact size, shape and degree of flexibility that is optimal was outside the scope of this contract and no additional funds have been awarded, so this remains an open question.

EFFECTS OF SWIMMING DURATION

As many Navy missions are of prolonged duration, we studied divers swimming to voluntary exhaustion. Our divers could only swim for up to two hours and then quit. These swimmers swam at 30 m/min which required a Vo_2 of about 1.2 l/min (50% Vo_2 max for swimming). During this period there were no significant increases in Vo_2, or Vco_2, while heart rate and ventilation decreased about 10%. The venous blood lactic acid increased by about 0.5 mM over the first 30 min and then remained constant until about 90 min, after which it rose to 1.2 mM. The final values was still below what is considered significant anaerobic metabolism (4.0 mM). The fact that fatigue set in when lactic acids in blood, heart rate, and ventilation were well below maximal levels demonstrates that the fatigue observed is a local one and most likely has to do with neuro-muscle fatigue or substright depletion. The latter explanation has to be considered as the R during the swims was between 0.8 and 0.9, which indicates that the subjects were using both inter-muscular fat and glycogen, either of which could be depleted over the 2 hr swim. Studies in running conducted in our laboratory have established the importance of intramuscular fat as a fuel and based on the data from this study those finding would be even more important to these divers. The extension of these experiments was outside the scope of this contract and not further funding was made available.

EFFECTS OF COLD AND PROTECTIVE EQUIPMENT

Swimming in water below what is comsidered thermal neutral requires the diver to wear protective gear. The nature of this gear could increase the energy cost of swimming. The two most common types of gear are wet suits and dry suits. We compared swimming at 20.3 to 35.6 m/min in a dry suit to a wet suit to no suit. To avoid changes in body temperature during swimming the water temperature was controlled for each condition so that the core temperature responses were identical.Although the energy cost of swimming in a wet suit was slightly greater than swimming with out a suit, the differences were not significant. The energy cost of swimming in the dry suit was 50% greater at 25.4,30.4, and 35.6 m/min than swimming with the wet suit or no suit. The dry suit caused a shift in body position and kick frequency that together resulted in the increased Vo2. By correcting the distribution of buoyancy the body position should be able to be corrected to the horizontal, and reduce Vo2.

The study described above was specifically designed to prevent body cooling by clamping core temperature. Two additional series of experiments were conducted where the core temperature was allowed to drop and the effects on swimming performance were determined.

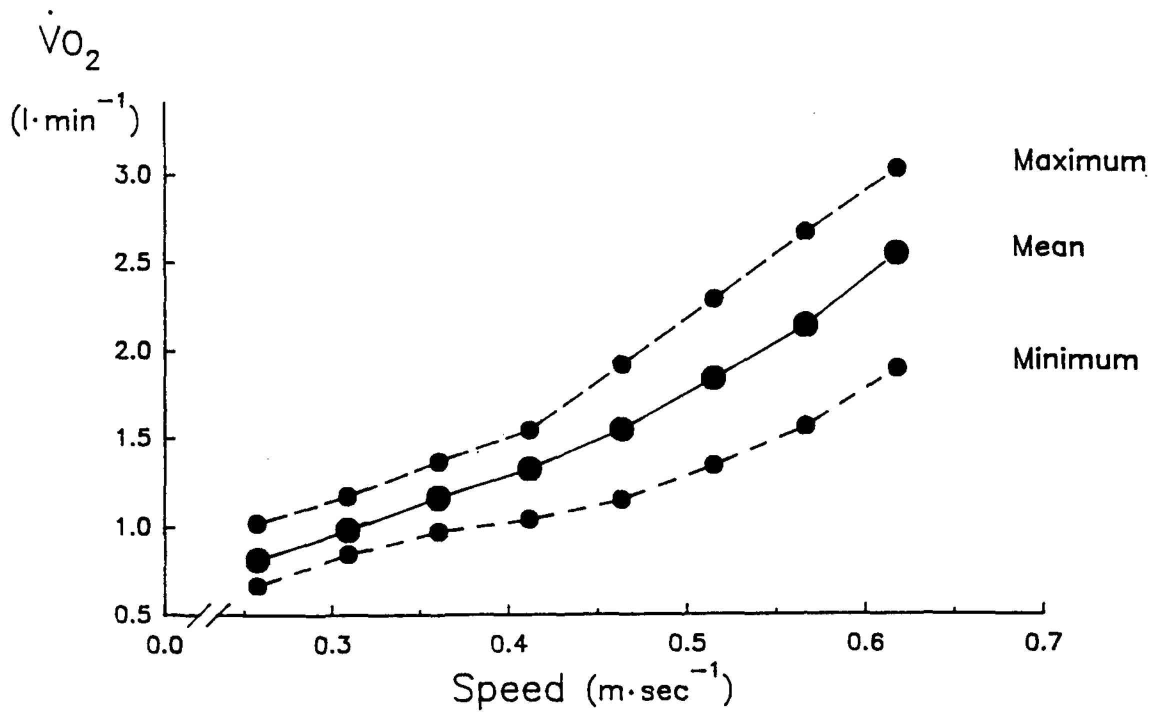
In the first series of experiments the divers were exposed to water temperatures of 35,30,25, and 20 during rest and exercise. Resting subjects (un-protected)have previously been shown to have significant body cooling below a water temperature of 30-32 degrees centrigade. This study demonstrated that exercising subjects could tolerate 25 degree C water without a decrease in core temperature. This tolerance was a result of a profound vasoconstriction due to decreased skin temperature. It is clear that, in addition to body fatness, the degree of vasoconstrictor tone and blood flow re-distribution are critical issues. These responses are highly individual, with some subjects lacking the ability to increase vasoconstrictor tone. The increased vasoconstrictor tone effects skin, as previously shown, but also effect the skeletal muscle. The result of this may be that in the peripheral, small, fixed muscle contractions like that used in fin swimming, local muscle fatigue would appear to be the major limitation to performance, as described above. The implications of the use of a dry suit or breathing pure oxygen may alter the vasoconstrictor tone, and consequently blood flow distribution, thermal balance and exercise tolerance. These factors were outside the scope of this contract and not funding was provided to pursue these modulations.

In the second series of experiments divers swam for up to 2 hrs. On one occasion the diver was protected and core temperature

protected. On the second occasion the diver was not protected, and their core temperature dropped by 1.0 degree C. Over the first 30 min of this swim there were no differences in Vo2, however as they continued to swim the Vo2 increased significantly in the cold. After 120 min the Vo2 was 30% higher. The blood lactate was significantly increased at 30 min, and increased to even a greater extent at 120 min (about 50% higher). Although the total body effects of this 1.5 mM increase in La are not significant, the local effect on a small group of exercising muscle is great. This further supports the role of local fatigue in limiting fin swimming, particularly in the cold.

SUMMARY

The energy cost of underwater swimming with a wet suit and SCUBA gear would appear to be about 40 l of O2 per kilometer swam. This value can be decreased with improved technique and gear selection and/or placement by as much as 50 %. The addition of larger gear increases the Vo2 by as much as 50 % while cold increases the value by as much as 30% (for 1 degree C drop in core temperature), and protective gear may increase to Vo2 by as much as 50 %. Placement of buoyant forces to keep the body horizontal during swimming can reduce the Vo2 by as much as 50 %. The combined effects of all of these factors could mean that Vo2 at a given speed could be 3-4 times above the 40 l/km, and require the diver to swim at very low speeds to keep far enough below their Vo2 max to tolerate long distance swimming.


VO2
(l·min−1)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.3
0.4
0.5
0.6
0.7
Speed (m·sec−1)
Maximum
Mean
Minimum

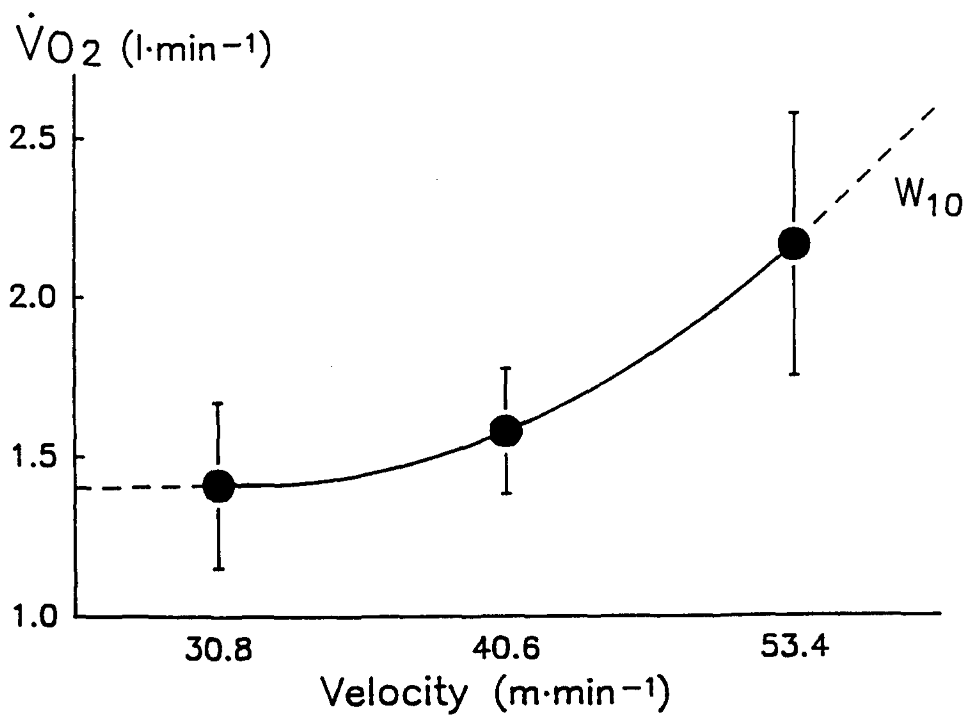

VO2 (l·min−1)
2.5
2.0
1.5
1.0
30.8
40.6
53.4
Velocity (m·min−1)
W10

FIGURE 1

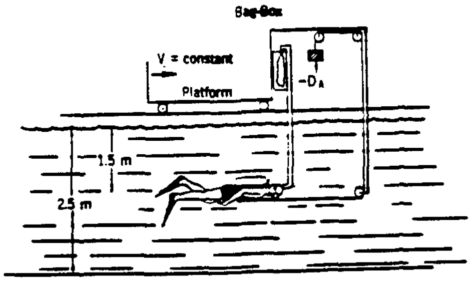


FIGURE 2

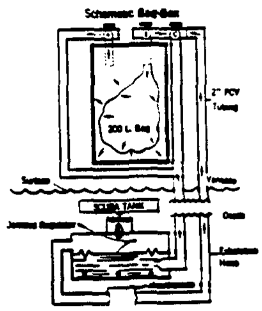
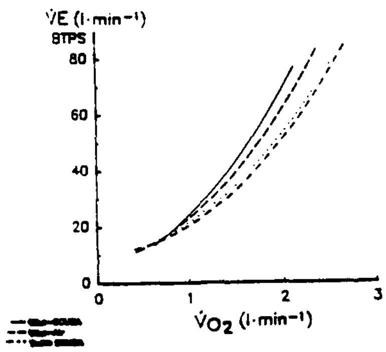


FIGURE 3



LEGENDS

Figure 1. A schematic representation of the monitoring platform, data collection system and the negative drag mechanism used in the SCUBA diving studies described in this paper.

Figure 2. A schematic representation of the pressurized Bag-in-Box gas collection system used in this study. Valve C opens and closes the diver from the bag-in-box. Valve B allows the bag to be filled by the subject or dumped to the dry gas meter. Valve A is used to pressurize the box to the same pressure as the diver is exposed to. The demand regulator is a two hose regulator with the PVC tubing connected in series.

Figure 3. The expired ventilation ($\dot{V}E$) is plotted as a function of oxygen consumption ($\dot{V}O_2$). The lines represent the line of best fit, fitted through the average ventilations observed during the 4 experimental configurations.

Figure 4. The net oxygen consumption is plotted as a function of swimming speed (v). The average values for the 4 groups of divers are shown. The dashed line and value are the $\dot{V}O_2/v$ ($\dot{V}O_2/d$) relationship fitted through all data. The data in the shaded area represent the data

Energetics of underwater swimming with SCUBA

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ABSTRACT

PENDERGAST, D. R., M. TEDESCO, D. M. NAWROCKI, and N. M. FISHER. Energetics of underwater swimming with SCUBA. *Med. Sci. Sports Exerc.*, Vol. 28, No. 5, pp. 573–580, 1996. Underwater swimming has unique features of breathing apparatus (SCUBA), thermal protective gear, and fins. The energy cost of underwater swimming is determined by the drag while swimming and the net mechanical efficiency. These are influenced by the cross-sectional area of the diver and gear and the frequency of the leg kick. The speeds that divers can achieve are relatively low, thus the $\dot{V}O_2$ increases linearly with values of $\dot{V}O_2 \cdot d^{-1}$ of 30–50 $l \cdot km^{-1}$ for women and men, respectively. Diving experience had little effect on $\dot{V}O_2$ for women; however, male divers with experience had lower $\dot{V}O_2$ than beginners. The location and density of the gear can alter the diver's attitude in the water and increase the energy cost of swimming by 30% at slow speeds. The type of fin used has an effect on the depth and frequency of the kick, thus on drag and efficiency, with a range of $\dot{V}O_2$ from 25 to 50 $l \cdot km^{-1}$. A large flexible fin had the lowest energy cost and a large rigid fin the highest. Adding extra air tanks or a dry suit increased the cost of swimming by 25%. The energy cost of underwater swimming is influenced by gender, gear and its placement, fin type, and experience of the diver.

OXYGEN CONSUMPTION, SCUBA SWIMMING, DIVING, DRAG, EFFICIENCY, FINS, BODY DENSITY

Swimming underwater presents the swimmer (diver) with several unique physiological problems (12). The first problem is that if the time of the dive exceeds breath-holding time, a source of ventilation has to be provided. The second problem is that the diver's body is exposed to a pressure that is proportional to the depth. To allow the diver to extend this depth and adjust automatically to changing depths, a self-contained underwater breathing apparatus (SCUBA) is typically used. This apparatus provides gas from a cylinder, carried on the diver's back, through a regulator to the lung at a pressure that compensates for the diver's water depth. It is important to recognize that hydrostatic pressure compresses gas volumes while not compressing fluid volumes. In general, man is positively buoyant when the lungs are full; therefore, the diver must carry weights that will allow him to "sink" underwater. The magnitude of the weight is dependent upon the positive buoyancy of the diver and his gear.

Diving is often carried out in water temperatures well below the thermal neutral water temperature of the individual, requiring the diver to wear a protective suit to provide additional insulation. As the water temperature and thermoneutral temperature of individual divers are variable, the type of protective suit needed also varies. The most widely used suit is a wet suit, which is tight fitting and usually made of neoprene. This suit provides insulation; however, it also increases the positive buoyancy of the diver and must be counterbalanced with weight.

Swimming underwater prevents the over-water recovery that is typical of surface swimming where propulsion is primarily provided by the arms. Therefore, during underwater swimming, propulsion is generally provided totally from a flutter type leg kick. Divers use fins to increase the surface area and allow effective propulsion, at least at slow speeds. Swimming fins have different physical characteristics, resulting in differences in propulsion effectiveness. Due to the extra equipment needed for underwater swimming, the water resistance (drag) may be greater than for surface swimming. In addition, the placement of the equipment could alter the swimmer's body position in relation to the horizontal (attitude) in the water and consequently, the drag. The swimmer's speed will affect the energy requirement. The swimmer's technical ability (skill) can significantly alter the energy cost of swimming (3,4,18). The energy requirement of underwater swimming would determine the potential time the diver could remain underwater since he is breathing from a fixed volume (size and pressure of the tank).

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The specific purpose of this article is to present selected factors that influence the energy cost of underwater swimming with SCUBA. The gear that was used in this study is typical of a sport diver and includes a mask, regulator, single tank, whole wet suit, fins, a deflated vest type positive flotation device, and weights placed at the waist. It is not the purpose of this article to evaluate the effectiveness of the gear from different manufacturers; however, reference is given to the physical characteristics of some of the gear studied. The experiments cited were conducted in thermoneutral temperature water. Although body cooling does affect the energetics, this is not the topic of this paper. As the unique nature of the environment and swimming affects the energetics, a discussion of the methods used of measuring precedes the section on the factors that may influence the energetics.

METHODS

Swimming is a unique form of exercise; however, the energetics can be expressed by the typical equations. Specifically:

$$\text{Power } (\dot{W}) = \text{Body Drag (Db)} \cdot \text{Velocity (v)}$$

$$\text{Energy Cost } (\dot{E}) = \dot{W} \cdot \text{Efficiency } (e)^{-1}$$

By equating units and rearranging these two equations, it can be shown that:

$$\dot{E} = \text{Db} \cdot v \cdot e^{-1}$$

The ratio of Db and e can be used as an expression of the technical ability or skill of the diver. This may also be expressed as the energy cost to swim a given distance ($\dot{V}O_2 \cdot d^{-1}$).

The velocity of swimming can also be expressed as:

$$v = \text{Kick rate } (\dot{S}) \cdot \text{distance per kick } (d \cdot S^{-1})$$

The distance traveled per kick ($d \cdot S^{-1}$) is determined, in part, by the propulsive force per kick, which is influenced by the type of fin, the diver's skill and the depth of the kick.

Using these simplified equations, one could measure the energy cost of swimming and understand its determinants by measuring Db, e, kick frequency, and kick depth. These parameters could then be used to evaluate the effects of various swimming styles, equipment or equipment placement on the energetics of swimming.

Energy Cost

The energy cost of terrestrial exercise and surface swimming can be assessed by open circuit measurement of oxygen consumption. The "anaerobic component" can be estimated from measurements of lactic acid (3,4). It should be recognized that there are difficulties in determining the anaerobic component from either muscle or blood lactic acid (1). Even the aerobic component is difficult to measure in underwater swimming as the diver

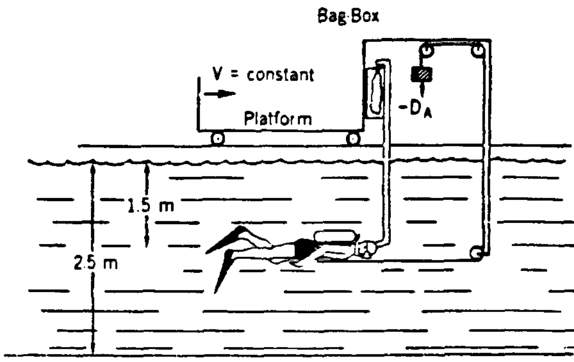


Figure 1—Experimental set-up for the annular swimming pool and monitoring platform. The bag-in-box gas collection system used in all experiments is shown. The method of deleting drag from the swimmer to determine drag and efficiency is shown.

is not only underwater and breathing compressed gas, but is also moving. Previous studies have used the difference in bottle pressure at the beginning and end of a swim (12,13) as a means to estimate oxygen consumption. No measurement of ventilatory volume and carbon dioxide output can be made using this technique. We devised a bag-in-box system to determine the energy cost of swimming to be used while the diver was paced at set speeds (Fig. 1).

Divers swam at a depth of 1.25 m in a 2.5 m deep annular pool (58 m in circumference). The divers followed a pacing mark, which was moved at a fixed and predetermined speed by a monitoring platform attached to a rotor. The breathing system was attached to the monitoring platform as shown in Figure 1. The breathing system was placed in parallel with the SCUBA breathing gear via a two hose demand regulator. The inspiratory hose was connected to the supply bottle via the pressure regulator. The expiratory hose was connected to a rigid tube (2-inch PVC), which went to the monitoring platform. This tube was connected to a valve that directed its flow either back to the expiratory side of the regulator (when not collecting) or to a bag (Douglas) placed inside a box (55 gallon drum) when collecting. During collection, the gas going into the bag displaces the gas in the drum (which is at the same pressure as the diver) and is exhausted through the expiration side of the regulator. Expired gas was collected from 1 to 3 min during the steady state of each fixed speed swim. The speeds were progressively increased. After each swim, the diver was isolated from the bag-in-box and the bag was emptied (using the pressure in the drum) through a dry gas meter. Samples of gas temperature, O_2 and CO_2, were made. The ventilation, oxygen consumption, carbon dioxide output, and expiratory gas exchange ratio were calculated using standard equations.

Previously, the bag-in-box method was validated by comparing the ventilation obtained by this technique and standard open circuit techniques during cycling and swimming. The relationship between $\dot{V}_E$ versus $\dot{V}O_2$ for

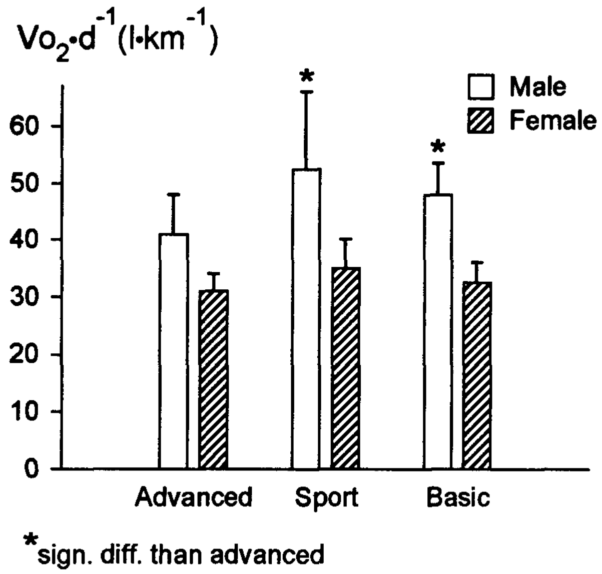


Figure 2—Mean ± SD for the energy cost of swimming 1 km from speeds of 0.4–0.54 m·min^{-1} for male and female divers with varying experience; * indicates values that are significantly higher than for the advanced men. The values for the women were significantly less than for the men; however, the values for the three levels of experience in the women were not different from each other.

the bag-in-box system and the open circuit technique were not significantly different from each other (ANOVA repeated measures, $P > 0.05$). The bag-in-box system would appear to be a valid method of determining gas exchange from submerged divers. The data reported in this paper used this method.

The bag-in-box method was used on subjects that were basic (inexperienced), sport (1 yr experience), advanced (>5 yr of diving), and professional (for at least 3 yr) divers. The $\dot{V}O_2$ increased linearly as a function of swimming velocity for all groups. The advanced divers had the lowest $\dot{V}O_2$, followed by the sport, then the basic. Interestingly, the professional divers had the highest $\dot{V}O_2$. This observation was surprising; however, the professional divers rarely swam in their jobs and were most likely similar to the basic divers in this regard. As $\dot{V}O_2$ increased linearly with v, the data can be expressed as the $\dot{V}O_2 \cdot d^{-1}$.

RESULTS

The energy cost of surface swimming has previously been shown to be less in women than men, even after correction for body size (18). This difference has been attributed to the differences in body density of the two genders, particularly in the lower extremities (14,17,18). Data for advanced, sport, and basic are shown in Figure 2. The female divers had significantly lower energy cost than the male divers for all skill levels. Although the male sport and basic divers had greater $\dot{V}O_2$ than the advanced divers, these differences were not seen for the female divers. These data would suggest that the body position in the water (attitude), as it affects the effective cross-sectional area, is very important and may be learned during diving training. This further suggests that the placement of buoyant and sinking forces may have a significant effect on the energy cost of swimming. From the practical point of view, when male and female divers are swimming together, the male divers will consume more oxygen, and therefore gas, resulting in shorter dive times.

Drag and Efficiency

In previous studies, the body drag during swimming (3,22) was determined by towing subjects through the water at increasing speeds. The force measured by a strain gauge was assumed to be equal to body drag. This measurement has become known as passive drag. The drag can be expressed as:

$$Db = kv^2 = \tfrac{1}{2} C_D p A v^2$$

where k is a constant, C_D is the coefficient of drag, p is the density of water, and A is the effective cross-sectional area.

The C_D (dimensionless) determined in the annular pool for a group of 12 male and female subjects (of varying sizes) who were towed in the prone position was 1.12 ± 0.06. Studies using photographic technique (strobe light) in a linear pool (22) yielded C_D values for the same group of subjects of 1.08 ± 0.04. The C_D values determined in the annular pool and the linear pool were not significantly different from each other (ANOVA for repeated measures $P > 0.05$). By calculation the correction force necessary to turn in a circle with the circumference of our annular pool would be less than 1%, which would agree with the comparisons of the C_D measured by the two techniques.

The results of the experiments to determine passive drag demonstrated that being towed at the surface has the greatest drag and towed at 1.25 m the least. Being towed at 0.6 m from the surface or at the bottom of the pool were not significantly different from each other, i.e., less than at the surface and more than at 1.25 m. This demonstrates the effect of the free surface (water surface or pool bottom) in increasing body drag. This also shows that when underwater swimming, one should stay greater than 0.6 m from all surfaces. In another series of experiments, subjects were towed prone and supine. The C_D for these conditions were 1.06 and 1.04, respectively. Body orientation would not appear to affect drag in an infinitely deep pool.

These values of passive drag are of interest when examining the effects of fixed aspects of gear or the environment. However, as the subject swims, the legs "open" and "close" with the kick, resulting in changes in the effective cross-sectional area and, therefore, drag. The drag can be expressed as an "effective" average drag (active drag). As has

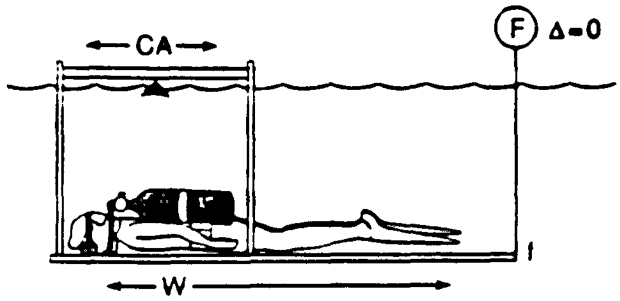
been previously shown for surface swimming, drag while swimming (active drag) is greater than passive drag (3). There could be an even greater effect during underwater swimming. To examine the active drag D, we used a method that we previously published for swimming (3,4). This method allows the calculation of body drag, efficiency, and the total energy cost of swimming (aerobic and anaerobic) while actually swimming. In principal, the subjects swim at a constant speed (paced by the monitoring platform, Fig. 1) towed by a vertical force (−DA) which is attached to the platform and then to the subject by a series of pulleys. Part of the subject's active body drag is overcome by the −DA, and consequently, the subject has to provide less propulsive force. The subject's $\dot{V}O_2$ is proportional to the propulsive force. By plotting the $\dot{V}O_2$ vs. the −DA, a linear slope is found. The slope of this line is the inverse of net mechanical efficiency. Extrapolation of this line to resting $\dot{V}O_2$ is the body drag. Extrapolation of this relationship to the y-axis yields the total energy cost of swimming at that speed. This technique has previously been validated for surface swimming (3,4) and we assume the validation holds for underwater swimming. This technique has the advantage that energy cost, regardless of mechanism (aerobic and/or anaerobic), can be estimated from submaximal $\dot{V}O_2$ data collections. This avoids the controversies regarding the meaning of muscle and blood lactic acid.

The values for the active drag are significantly greater than for the passive drag and the shape of the curve is different. In active diving, the drag is very high at low speeds (for each group), decreases at medium speeds, and then increases at higher speeds. The reason for these differences can be seen from an examination of kicking frequency and depth. At low speed, the diver used a slow and wide kick (high drag). At medium speed, the diver increased the kicking frequency and his kick became more narrow (less drag). At high speed, the frequency was high and the depth of the kick wide (high drag). If this analysis is correct, we would expect a high efficiency (10,15) when the frequency was low (low and high speed) and a low efficiency where the frequency was high (medium speed). This is what was observed.

Effect of Body Position

Body size and shape play an important role in determining the energy cost of surface swimming and undoubtedly underwater swimming. However, swimming technique and the distribution of body mass have been shown to be more important factors (2,11,14,15). Subjects supine at the water surface rotate about the mid-thorax ("center of air") with a torque that is determined by their mass and its distribution along the long axis of the body. In these experiments, as torque increased, the energy cost of swimming increased proportionally (11,14,15).

As discussed above, the effective cross-sectional area has an effect on drag. The effective cross-sectional area was shown to be affected by kick depth and velocity. These effects would be altered by the attitude of the diver. The application of these data to SCUBA swimming is even more interesting than surface swimming, due to the potential effects of the gear on torque. To test this hypothesis, men SCUBA divers were studied. Precalibrated lead weights of known mass were applied to each subject by means of a weight belt. The six experimental configurations were delineated in the following manner: Condition 1) 44 N at the "center of air," 2) 0 N at the "center of air" and 44 N on the waist (normal configuration), 3) 44 N on the waist and 22 N on the knee, and 4) 44 N on the waist and 22 N on the ankle. Subjects' "center of air" and torque were determined experimentally through a method of underwater weighing (see Fig. 3).



$$\tau = F_f \cdot d_{ca\text{-}f}$$

Figure 3—The schematic representation of the experimental set-up used to measure underwater torque. The divers lay prone underwater on a rigid frame. This frame was supported by another frame that was above the water and was supported by a fulcrum (▲). Torque is calculated as a function of the force measured at the feet (F) and the distance from F to the "center of air" (CA). The "center of air" was experimentally determined for each subject by varying the position of the fulcrum until there was no change in F.

The rotational forces about the "center of air" (torque) for the weight placements used in this study are shown in Figure 3.

The subjects were firmly attached to a frame (0.7 m × 2.4 m) by quick-release belts and submerged 10 cm below the water surface while breathing through SCUBA gear. The frame and subject were supported by a fulcrum placed under the "center of air." Force was measured by a strain gauge (LVDT) at the "foot" of the frame. The "center of air" was determined for each subject by positioning the fulcrum at the point where variations in lung volume affected foot force the least. Torque (Nm) was calculated as the product of foot weight and the distance between the strain gauge attachment and "center of air." This system measured the "tendency of the feet to sink" from the horizontal position by determining the force necessary to maintain a horizontal position in the water. As weight was progressively redistributed away from the "center of air" and toward the ankle, there was a progressive increase in torque. The maximal value of torque was observed when 44 N was added to the waist with an additional 22 N on the ankles.

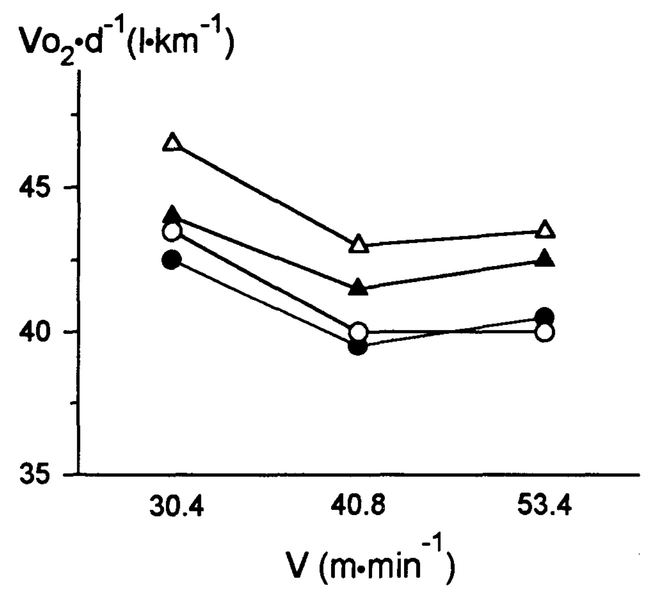


Figure 4—The energy cost of swimming per kilometer are plotted as a function of swimming speed for increases in torque. The increases in torque were produced by distributing the divers' weights from the "center of air" to the waist and then knees and ankles. There was a significant increase in $\dot{V}O_2 \cdot d^{-1}$ as torque was increased (● to ○ to ▲ and to △).

The energy cost to swim a given distance is plotted as a function of swimming speed in Figure 4. The $\dot{V}O_2 \cdot d^{-1}$ was greatest at the slowest speed studied and not significantly different between the two faster speeds. The effect of changing torque was to increase the $\dot{V}O_2 \cdot d^{-1}$, particularly when the torque was increased by adding weight to the knee and/or ankle.

The torque of the body, plus equipment, causes the body to rotate about the "center of air." Thus, the greater the torque, the less horizontal the subject is in the water. The deviation from the horizontal increases drag unless the subject kicks harder to keep the body horizontal, which would result in reduced efficiency and increased $\dot{V}O_2$. At the slow speed, reducing torque resulted in an attitude in the water that was closer to horizontal than conditions with increased torque (28° and 35°). At the faster speed, there were no significant differences between the weight placements. This may be due to the fact that at the faster speeds, the angles were less than at the slower speeds (29° and 22° vs 35°) and the torque-dependent effect was minimized.

The energy cost of underwater swimming was dependent upon both speed (2,5,6,7,9,13,15,16,20,21) and weight placement (11). This is important for divers swimming at slow speeds, where the rate of energy requirement is not important; however, the total cost is. The $\dot{V}O_2$ increased with speed; however, the $\dot{V}O_2 \cdot d^{-1}$ was greatest at the slowest speed (0.16 $l \cdot km^{-1}$ to 0.22 $l \cdot km^{-1}$) and similar at the two faster speeds (0.14 $l \cdot km^{-1}$ to 0.17 $l \cdot km^{-1}$ and 0.14 $l \cdot km^{-1}$ to 18 $l \cdot km^{-1}$, respectively). For longer distances, it would appear that one could conserve energy by swimming at 40.8 $m \cdot min^{-1}$, instead of 30.4 $m \cdot min^{-1}$ or 53.4 $m \cdot min^{-1}$. This effect was true at all levels of torque.

Propulsion in fin swimming is achieved by a combination of the force per kick, which is related to the depth of the kick, and the frequency of kicking. With the weights placed at the waist, the subjects had a kick frequency of 39 $k \cdot min^{-1}$, 47 $k \cdot min^{-1}$ and 59 $k \cdot min^{-1}$ and a depth of 40.6 cm, 46.4 cm and 43.2 cm at speeds of 30.6 $m \cdot min^{-1}$, 40.8 $m \cdot min^{-1}$ and 53.4 $m \cdot min^{-1}$, respectively. Swimming speed is increased, in part, by increasing kick frequency (about 0.8 kicks per $m \cdot min^{-1}$). As speed was increased from 30.6 $m \cdot min^{-1}$ to 40.8 $m \cdot min^{-1}$, kick depth increased; however, at the faster speed, the depth could not be sustained due to the higher kick frequency and, therefore, the depth decreased (35.6 cm, 45.7 cm, and 42.3 cm, respectively).

The effect of weight placement on kick frequency and kick depth was velocity-dependent. At the slowest speed where there was freedom to alter kick frequency and kick depth, reducing torque resulted in a decrease in both kick frequency (39 $k \cdot min^{-1}$ to 33 $k \cdot min^{-1}$) and kick depth (40.6 cm to 21.1 cm). At the two faster speeds, there were no significant differences between the values. Increasing torque did not significantly affect either kick frequency or kick depth.

Fin Selection

As described above, the subjects' kicking frequency and depth of kicking with fins determines their propulsive force, velocity, and therefore their $\dot{V}O_2$. In addition, SCUBA swimming also may require stabilization in the water, towing objects, swimming fast away from or toward something in an emergency, and/or swimming to conserve energy (12). The fin characteristics would alter the divers' performance and their resultant energy cost. Many types of fins are available and used routinely. Divers' fin preference is largely subjective. Despite manufacturer's claims, little data are available to evaluate the effectiveness of fins to meet the performance needs of the divers.

Previous studies have reported the energy cost of swimming with fins against a tether (16), free swimming at various speeds (5,6,10,13,20), or free swimming against a drag device (7,19). When combined, these data demonstrate a $\dot{V}O_2$ of about 0.8 $l \cdot min^{-1}$ at 15 $m \cdot min^{-1}$, increasing with speed up to 2.5 $l \cdot min^{-1}$ at 30 $m \cdot min^{-1}$. In another study, the relationship between $\dot{V}O_2$ and speed of fin swimming showed that the surface area of the fin was inversely related to the $\dot{V}O_2$ and that the maximal swimming speed was directly related to fin flexibility. High levels of $\dot{V}O_2$ are achieved in elite divers swimming against maximal tethering, up to about 4.0 $l \cdot min^{-1}$.

Studies using commercially available fins with different characteristics of size, weight, flexibility, and material composition are presented. A comparison of the

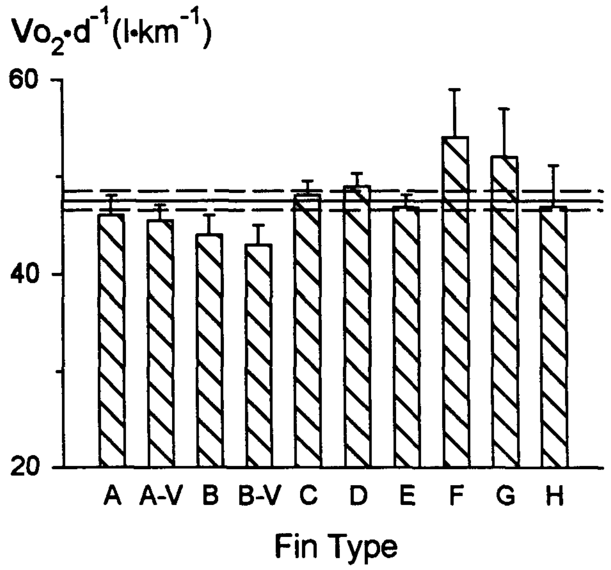


Figure 5—The energy cost of swimming 1 km for men is plotted as a function of fin types. The fin types are described in Table 1. There were no significant differences in fin type across all subjects, however the values varied from 43 to 54 l·km^{-1}. Fins with vents (A-V and B-V) were not significantly different for the same fin without vents (A and B).

TABLE 1. Characteristics of the 10 fins discussed.

Fin	Weight (kg)	Flexibility	Surface Area (cm^2)	Vents
A	1.59	(rigid)	239	No
A-V	1.14	(mod)	240	Yes
B	1.82	(rigid)	253	No
B-V	1.36	(mod)	235	Yes
C	1.14	(mod)	222	Yes
D	0.90	(flex)	175	No
E	0.98	(rigid)	294	Yes
F	0.98	(mod)	294	Yes
G	1.20	(rigid)	264	No
H	1.23	(flex)	285	No

mod, moderate; med, medium; flex, flexible.

effects of fin type selection on the energy cost of swimming for males appears in Figure 5. The data for the male divers failed to show a significant difference among the 10 fin types while swimming. The data for the female divers demonstrated significantly lower (20%) energy cost of swimming than men. For women, the small, very flexible fin (D) required less energy to swim (30 l O_2·km^{-1} vs. 32 l O_2·km^{-1},33 l O_2·km^{-1},34 l O_2·km^{-1},35 l O_2·km^{-1} and 39 l O_2·km^{-1} for D vs A-V, C, B-V, A, and B, respectively). The vented fins (A-V, B-V) were less costly than the unvented fins (A, B). The least effective fin for the females was the large, rigid fin (B).

The frequency of leg kicking during steady state swimming was not significantly different between the 10 fins for males or females. The average value for kick frequency for all males and females was 42 ± 2 k·min^{-1}. The relationship between the energy cost of swimming per unit distance and kick frequency was not statistically significant.

The average maximal speed that could be sustained for 58.6 m using the fins studied was greater for the men than for the women (1.29 ± 0.32 m·s^{-1} vs 1.24 ± 0.16 m·s^{-1}, respectively). The speeds for males with all unvented fins were not significantly different from each other. However, the vented fins (A-V, B-V, E, F) were significantly slower when compared to their unvented counterparts. For the females, the medium, rigid fin (A) was the fastest. However, a medium, moderately flexible fin (C) achieved a similar speed. The vented fins (A-V, B-V) and a large, rigid fin (B) had the slowest speeds for females.

The maximal force that could be generated by males was with the medium and large, rigid, unvented fins (A, B), with significantly lower maximal forces generated with the vented fins (A-V, B-V), the medium, moderately flexible fin (C), and the small, very flexible fin (D). For the females, the vented fins (A-V, B-V); the large, rigid fin (B); the medium, moderately flexible fin (C); and the small, very flexible fin (D) were not different from each other and produced lower maximal force than a medium, rigid fin (A). The decrease in force over the 40 s of the swim was not significantly different among the fins or between the genders and averaged 12.5% ± 3.8% of the maximal force.

Evaluation of the kick frequencies used for each fin during the tethered maximal force swim showed that for the males, the medium, moderately flexible, vented fin (A-V) and the small, very flexible fin (D) had the greatest frequencies, followed by the medium, moderately flexible, vented fin (B-V) and the medium, moderately flexible fin (C). The medium and large, rigid fins (A, B) had the lowest kick frequencies. For the females, the medium and large, rigid fins (A, B) had the lowest frequencies, while the same fins vented, the medium, moderately flexible fin (C) and the small, very flexible fin (D), were significantly higher.

Subjectively, the males and females preferred a large, rigid fin. There was no systematic preference for the vented fins. The medium, moderately, or very flexible fins had the most comfortable foot pockets.

There was a significant difference in weight between the two pairs of heavy fins and the two pairs of light fins (C and D, A and B, respectively). Swimming with one of the heavier fins (D) produced a lower $\dot{V}O_2$ than a lighter fin (B), indicating that the weight of the fin did not alter the divers' $\dot{V}O_2$ at either speed. Similarly, the presence of vents did not appear to affect $\dot{V}O_2$. At 30 m·min^{-1}, two pairs of fins (vented (A) and unvented (B)) produced a significantly lower $\dot{V}O_2$.

Propulsion is a product of kick frequency, kick depth, and force per kick. Force per kick was not measured in this study. There were no significant differences in the kick depth for any of the fins at either speed or between speeds (43.18 ± 12.7 cm). Kick frequency was higher at 40 m·min^{-1} than at 30 m·min^{-1} for all fins (46 ± 7 k·min^{-1} vs 35 ± 5 k·min^{-1}, respectively). The heavy, very flexible fin (D) produced a significantly lower kick frequency (31 ± 7 k·min^{-1}) than the other fins, which were not significantly different from each other (35 ± 5 k·min^{-1}).

One of the advantages of the present study was that the expired ventilation, carbon dioxide production, and $\dot{V}O_2$ could be determined. The $\dot{V}_E/\dot{V}O_2$ ratio was not significantly different among fins or speeds and averaged 19.52 ± 1.98. The expiratory gas exchange ratio ($\dot{V}CO_2/\dot{V}O_2$) was not significantly affected by fin type or speed and averaged 0.87 ± 0.24, although the range among the subjects was 0.77–0.96. The ventilatory equivalent of 19 is less than reported for exercise in air, 25. This suggests some CO_2 retention, producing an R value less than RQ. The faster speed used for steady state swims was 75% of the maximal speed, which is below the threshold where the $\dot{V}_E/\dot{V}O_2$ ratio would increase due to lactic acid in the blood (4).

Effects of Other Gear

The experiments described above were conducted using standard sport diving gear. Divers that prolong their diving time may use dual gas tanks. As the energy cost per unit distance of swimming at slow speeds is quite high, the addition of a second tank had little effect. At faster speeds however, the effect became pronounced as the second tank and its position significantly increased drag and, therefore, $\dot{V}O_2$. Similar results were seen when the divers wore a dry suit. There was no effect on $\dot{V}O_2$ at the lowest speed; however, it did have a significant effect at the faster speed. The conclusions from the present study are in agreement with previous studies for wet (5,7,10,13,15,22) and dry suits (19). It would appear that the data from the present study are more accurate due the method of collection and direct comparison for individual subjects.

CONCLUSIONS

The data presented in this article demonstrated that the energetic analysis used previously for swimming can also be applied to underwater swimming. The method of measurement of ventilation, oxygen consumption, and carbon dioxide production is a valid measurement. The data for ventilation during underwater swimming demonstrated a relative hypoventilation when compared with terrestrial locomotion.

The oxygen consumption for underwater SCUBA swimming was affected by the placement of the weight belt that was used to counterbalance the buoyancy created by the gear worn by the diver. To minimize the energy cost of swimming, divers should strive not only for neutral buoyancy but also equipment placement that keeps them in a horizontal position in the water. The energy cost of swimming for women was significantly less than that for men, even after correction for body size. However, this difference disappears when the men adjust their body position to be more horizontal by appropriate placement of their diving weights.

The oxygen cost of swimming at a given speed is determined by the ratio of active drag and overall net mechanical efficiency. Active drag and efficiency are influenced by speed ($Db = kv^2$) and the body position in respect to horizontal as well as the depth of the kick. Mechanical efficiency was shown to be related to the kicking frequency. Divers should determine a balance between kicking frequency and kicking depth (fin exertion) that will minimize drag and maintain efficiency. It is clear from the data presented that swimming skill can influence, to a great extent, the energy cost of swimming and that experienced divers can minimize their energy expenditure. The addition of more gear, like double tanks or dry suits, increases the energy cost slightly at lower speeds. However, at higher speeds, the effects are very large and limit performance.

The selection of a fin type to use in diving was shown to be very subjective and based on the swimmers' "feel." The large rigid fins required a greater force to kick and were preferred by the divers (particularly the men). In fact, the similarity of the energy cost, speed, and force that the fins could generate was more striking than their differences. The large and rigid fins had the highest energy cost; however, they produced the greatest force. This suggests that the best fin selection may be based on the task the diver has to accomplish. For swimming, it would appear that a medium sized and flexible fin would be the best. The new composite material and venting did not seem to have significant effects on the energy cost.

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Defense Technical Information Center
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ATTN: Pat Mawby
Ft. Belvoir, VA 22060-6218

Dear Pat:

Please find enclosed the final progress report for ONR grant Nooo-89-0103 Titled " Diver's swimming efficiency as a function of buoyancy, swimming attitude, protective garments, breathing apparatus, swimming technique and fin type". This report was filed on December 15, 1993 with Dr. Schibly, Program Manager, Submarine & Diving Medicine, Naval Medicine Research and Development Command, National Naval Medical Center, Bethesda, MD 20889-5044. I have also include a copy of a paper that was published that should be an appendix to this report.

I hope this is the information that you need, if not please let me know.

Sincerely,

David R Pendergast

David R. Pendergast
Professor and Associate Director CRESE

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